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Validation Test Results for Orthogonal Probe Eddy Current Thruster Inspection System

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Background

Recent nondestructive evaluation efforts within NASA have focused on an inspection system for the detection of intergranular cracking originating in the relief radius of Primary Reaction Control System (PCRS) Thrusters [1-3]. Of particular concern is deep cracking in this area which could lead to combustion leakage in the event of through wall cracking from the relief radius into an acoustic cavity of the combustion chamber. In order to reliably detect such defects while ensuring minimal false positives during inspection, the Orthogonal Probe Eddy Current (OPEC) system has been developed. The technique incorporates a dual frequency, orthogonally wound eddy current probe mounted on a stepper motor controlled scanning system. The system is designed to inspect for outer surface damage from the interior of the thruster. As the outer surface of the thruster is inaccessible without extensive disassembly, this enables on vehicle or routine depot level inspection of thrusters for relief radius intergranular cracking. A more detailed description of the OPEC technique is contained in a previous report [1].

System Validation

In order to verify the reliability of the OPEC system an extensive validation including blind inspection of over 1500 acoustic cavities was performed. Validation testing was conducted at United Space Alliance (USA) facilities in Cape Canaveral Air Force Station by USA eddy current level II NDE inspectors. Prior to the beginning of the inspections, two days of training consisting of a system overview, demonstration, and hands on practice was provided to the inspectors by the system developer. Demonstration and hands on work was performed on a sample set consisting of an oil-bronze thruster replica with fabricated flaws as well acoustic cavities 25 – 29 of PRCS thruster serial number 713. Following training, three United Space Alliance (USA) eddy current level II NDE inspectors were tasked to inspect the validation sample set. These inspections were performed in accordance with written procedures documented in the validation plan [4,5]. Flaw calls were made immediately by the inspectors and documented on inspection reports. All raw data were also saved for further analysis.

Validation Sample Set

Four PRCS thrusters, three of which contained fabricated electric discharge machine (EDM) notches, were used for this validation study. Table 1 reports the location, remaining wall thickness, and angle of the flaw with respect to mounting flange for each of the fabricated EDM notches. The first 11 notches were placed directly across from the indicated acoustic cavity while the final 7 notches were placed between the two adjacent cavities identified in the table. The resulting flaw population contains 18 independent flaws approaching 25 acoustic cavities. The fourth thruster used in the validation study contained no flaws. As each thruster contains 42 acoustic cavities, the sample set of four thrusters contained 143 unflawed inspection sites. The complete validation sample set was inspected three times by each of the three level II NDE inspectors for a total of nine

inspection cycles. The complete validation inspections therefore resulting in 225 scans of cavities with approaching flaws and 1287 scans of unflawed cavities. Neglecting the 5 inspection sites used for training and calibration, the condition of the thrusters was not known to the inspectors.

Table 1. Manufactured Flaws in Validation Standards

Thruster S/N	Acoustic Cavity	Remaining Wall Thickness (in)	Flaw Angle (degrees)
714	16	0.02	30
451	27	0.02	45
713	37	0.02	60
451	32	0.04	30
714	32	0.04	45
451	37	0.04	60
714	27	0.02	45
714	37	0.06	45
713	27	0.03	45
713	32	0.06	45
713	16	0.04	45
714	10/11	0.02	30
451	42/1	0.02	45
713	42/1	0.02	60
713	5/6	0.04	30
714	5/6	0.04	45
713	10/11	0.04	60
451	5/6	0.06	45

Inspection Results

Flaw calls were reported by the inspectors immediately following the scan of a given cavity. This call data along with specific inspection criteria and all raw data were then recorded before the next cavity was inspected. Figure 1 displays a plot of the flaw call results. In this plot the hit ratio for flaws at each remaining wall thickness is calculated as the number of flaw calls divided by the number of opportunities to detect flaws of that remaining wall thickness. All unflawed cavities are plotted at a thickness of 0.145”, the approximate minimum wall thickness between the relief radius and acoustic cavity in the absence of any flaws. All inspections at sites with 0.020” and 0.030” remaining wall thicknesses were called along with 89/90 0.040” remaining wall thickness sites and 18/36 0.060” flaw sites. No false positives were reported from any of the unflawed cavities.

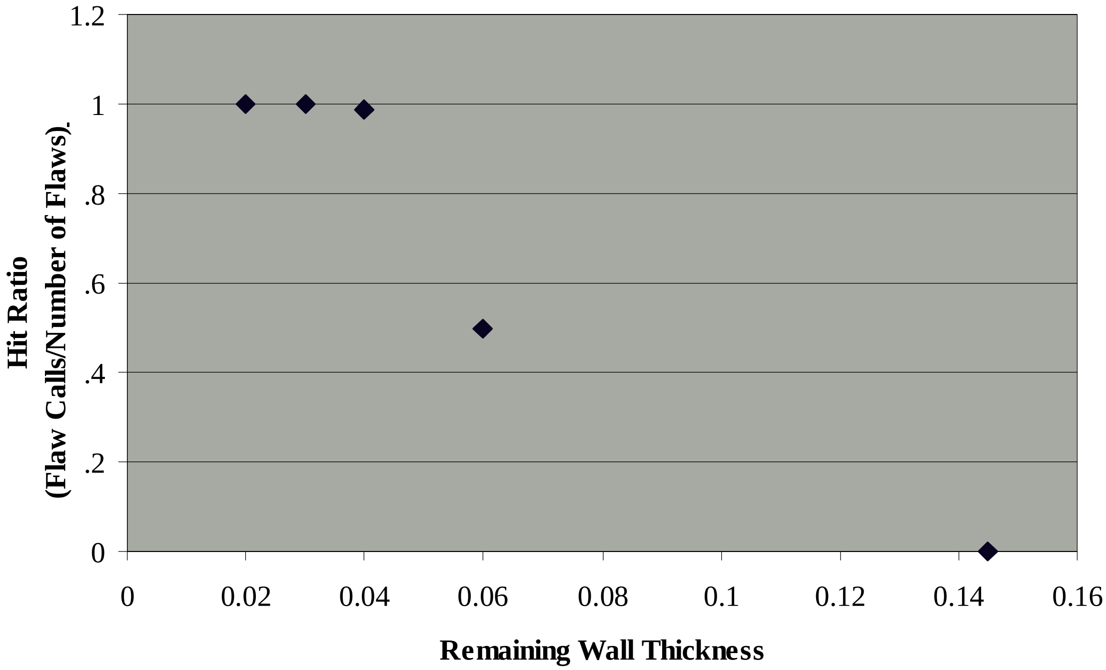

Figure 1. Hit ratio for flaws at all 1512 cavities inspected during validation testing.

A closer look at the data reveals additional information concerning the undetected flaws. Strong evidence exists that the one missed call at 0.040” remaining wall thickness is due to a missed inspection site rather than a missed call at the site with 0.040” remaining wall thickness. It appears a duplicate inspection was performed on the cavity prior to the cavity in question (S/N 713, AC16) which was then skipped over on the next inspection. All other inspections of S/N 713 AC 16 produced strong flaw response. The remaining missed calls all occurred at the sites corresponding to the 0.060” remaining wall thickness flaw originating between adjacent acoustic cavities (S/N451 AC5-AC6). The two flaws with 0.060” remaining wall thickness which originate directly across from the acoustic cavity (S/N 713, AC32 and S/N 714 AC37) were detected in every inspection cycle.

Another method for examining the validation test results is to plot the system response versus remaining wall thickness. The data fall into two main clusters depending upon the orientation of the flaws. Figure 2 displays the results for all flaws originating across from an acoustic cavity. The plot contains the results from all nine inspection cycles. The indication level for all unflawed cavities is shown as the cluster of points at 0.145” remaining wall thickness. The single missed inspection at S/N713 acoustic cavity 16 (0.040” remaining wall thickness) is clearly out of family with the remainder of the data and, as discussed above, is the result of a missed inspection of that site. Otherwise the data show a strong correlation between indication strength and remaining wall thickness with a clear distinction between all flawed and unflawed cavities. An indication strength of 0.5 volts was set by procedure to be the threshold for a relevant flaw indication [3].

All Notches Across From Cavities

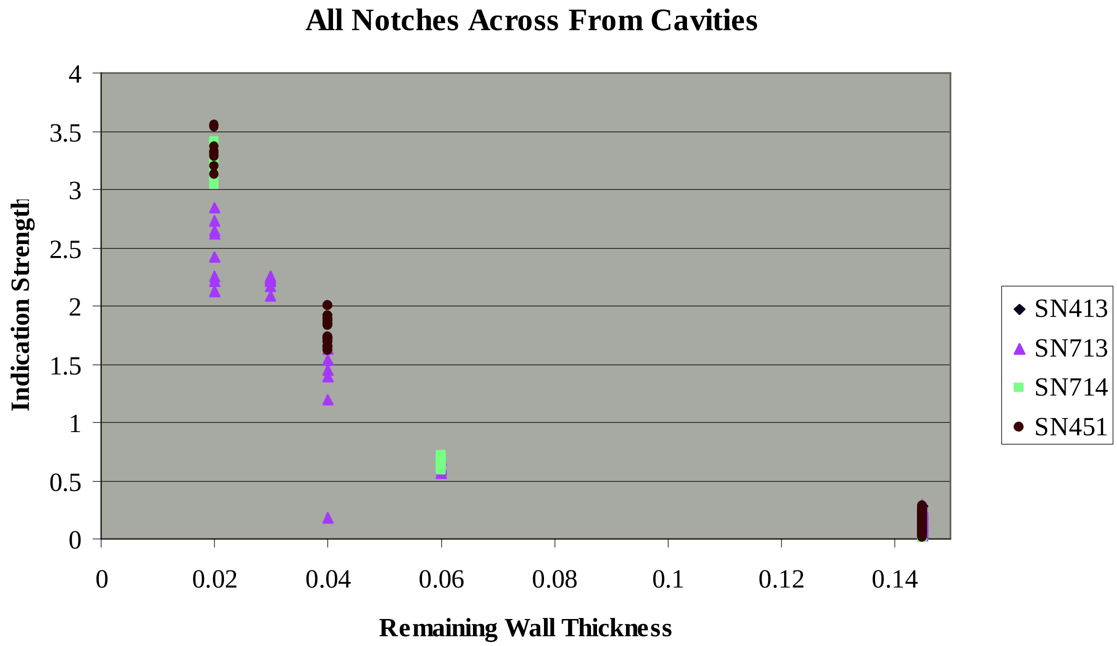

Figure 2. Indication strength for all notches originating across from an acoustic cavity.

Figure 3 displays the results for all flaws originating directly between acoustic cavities. As in figure 2, the plot contains the results from all nine inspection cycles. A drop in the indication level as compared to flaws originating across from the cavities is evident. The indication level for between cavity flaws at 0.060" remaining wall thickness overlaps the distribution for the unflawed cavities. All flaws within 0.040" of the cavity are clearly separated from the unflawed cavities and were detected in the study.

Another factor which was found to influence the measured indication strength is the angle of the flaw with respect to the thruster mounting flange. As reported earlier, flaws

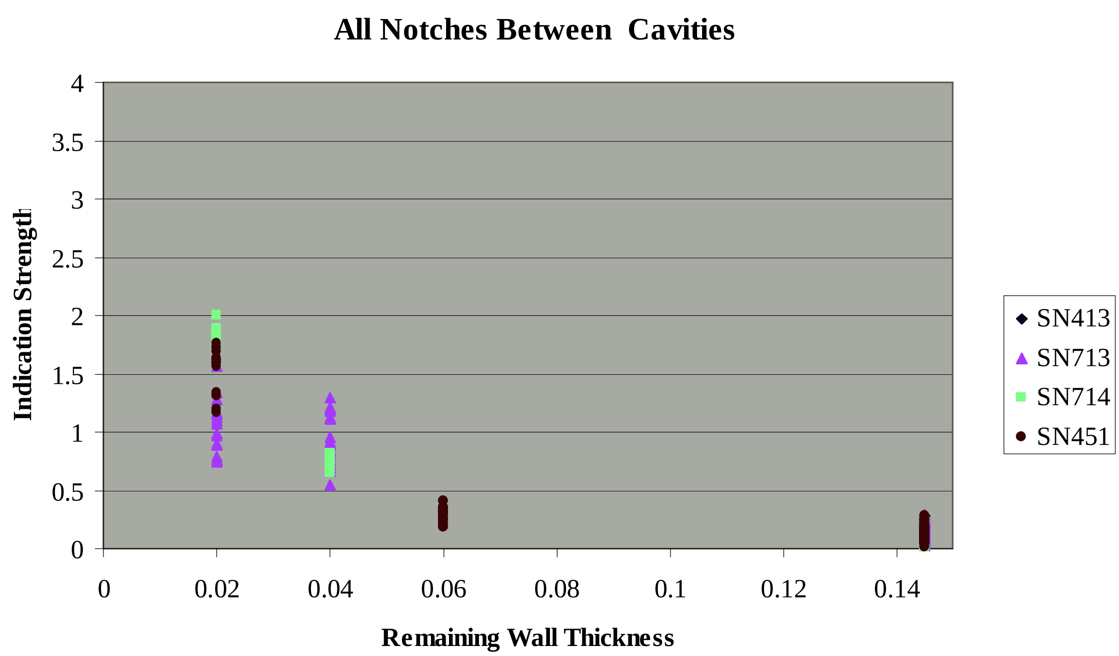

Figure 3. Indication strength for all notches originating between adjacent acoustic cavities.

were introduced at angles of 30, 45 and 60 degrees. While the 30 and 45 degree flaws showed a similar response to the inspection system, edge effects associated with the proximity of the 60 degree flaw tip to the thruster face resulted in slightly reduced detection sensitivity. It should be noted that such high angle flaws appear to be rare. Destructive analysis performed by the NASA Engineering and Safety Center on PRCS Thruster S/N 132 found flaw angles to be typically between 40 and 50 degrees with a maximum measured flaw angle of 54 degrees [6].

In figures 4 the 60 degree flaws have been removed to show the strong correlation between remaining wall thickness and indication strength for the 30 and 45 degree flaws originating across from an acoustic cavity. The missed inspection at S/N 713 AC 16 has also been removed for clarity. Figure 5 shows the equivalent data for flaws originating between adjacent acoustic cavities. Here the plotted indication strength is the average of the recorded signal from the acoustic cavities on either side of the flaw. Averaging these values helps to correct for potential misplacement of the flaw between the cavities.

Relationship Between Validation Artifacts and PRCS Thruster Cracking

The applicability of electric discharge machine notches to simulate naturally occurring cracking in PRCS thrusters for the development of nondestructive evaluation standards has to be taken into account to predict the detectable size of such damage. To this end a limited number of intergranular cracking sites previously identified in PRCS thruster S/N 132 have been maintained for NDE development and system calibration. As realistic flaws are difficult to fabricate, especially in statistically relevant quantities for NDE system validation, validations are typically performed with fabricated notches. A (knockdown) factor describing the response of the system between the validation artifacts and actual flaws is then sought to bound the flaw detectability on real hardware.

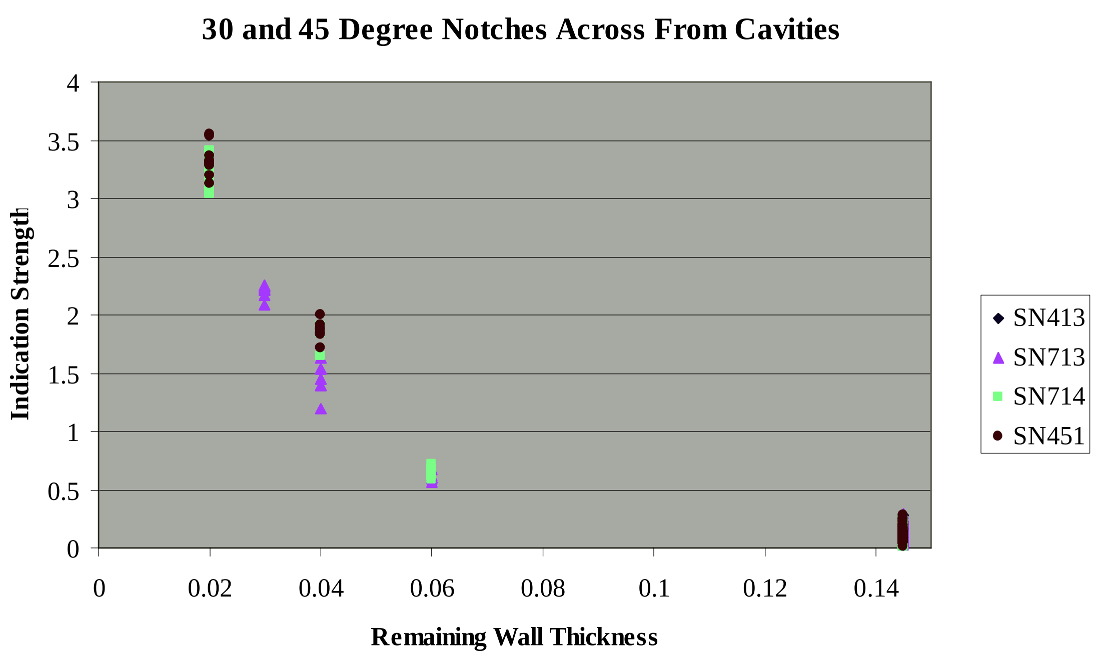

Figure 4. Indication strength for 30 and 45 degree notches originating across from an acoustic cavity.

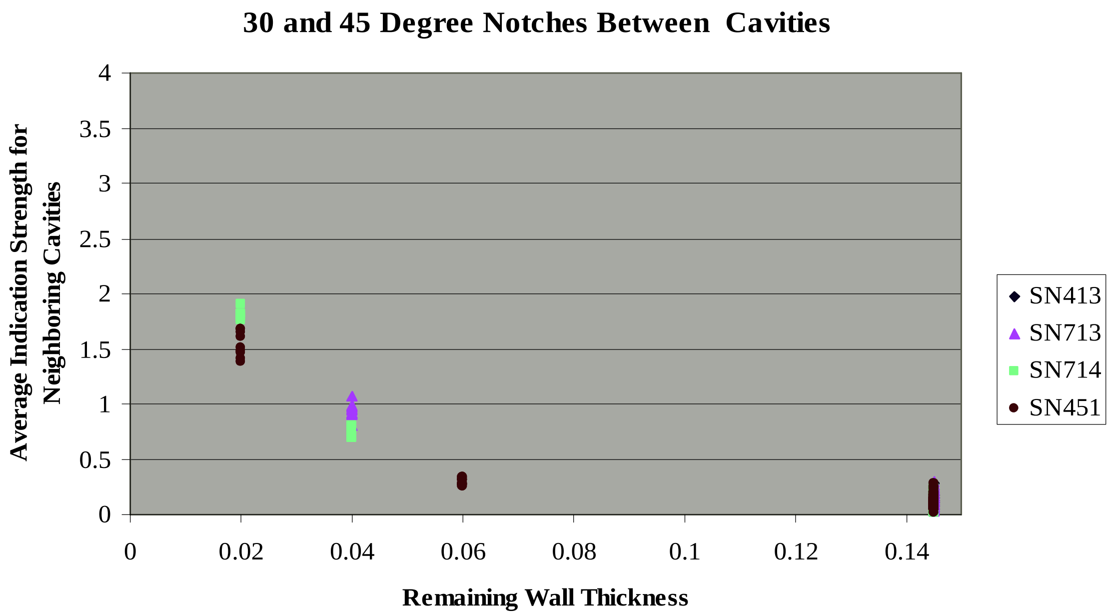

Figure 5. Inspection Results for 30 and 45 degree notches originating between adjacent acoustic cavities. Indication strength calculated from average of cavities on either side of notch.

In this work the eight remaining inspection sites on PRCS Thruster S/N 132 were examined with the OPEC system. As describe in the NESC Report [6], sections of this thruster have been destructively examined and crack depths measured. Figure 6 displays the indication levels from this naturally occurring damage along with measured crack depths. The data acquired from acoustic cavities 37 and 38 each showed saturation in the low frequency (12 kHz) response along with a very strong vertical response in the high frequency (100 kHz) data. As the standard depth of penetration of the electromagnetic field in the thruster is approximately 0.070" at 12 kHz but only approximately 0.025" at 100 kHz, this indicates that the discontinuity in the material extends very close to the acoustic cavity wall and is potentially a through wall flaw in these locations.

By extrapolating the measured crack depths from the destructive analysis of S/N 132 through an area with a preseved acoustic cavity an approximation of the remaining wall thickness at the OPEC inspeciton site can be determined. Figure 7 plots the extrapolated remaing wall thickness in thruster S/N 132 versus indication strength for the OPEC system inspections. The responses from acoustic cavities 37 and 38 have been removed from the plot due to system saturation at these inspection sites. Figure 7 also contains the data for the 30 and 45 degree notches placed across from an acoustic cavity. The data show that the signal level from naturally occurring damage is comparable to, or even higher, than that for the validation notches. A likely cause for the increased signal levels on naturally occurring damage is the flaw profile. All naturally occurring damage identified to date has shown a very high aspect ratio of crack length to crack depth. The notch standards were all fabricated with a two to one aspect ratio, and therefore likely underestimate the crack length at a given remaining wall thickness. The likely flaw aspect ratio also minimizes the potential for deep cracking between acoustic cavities without appreciable damage directly in front of a single cavity.

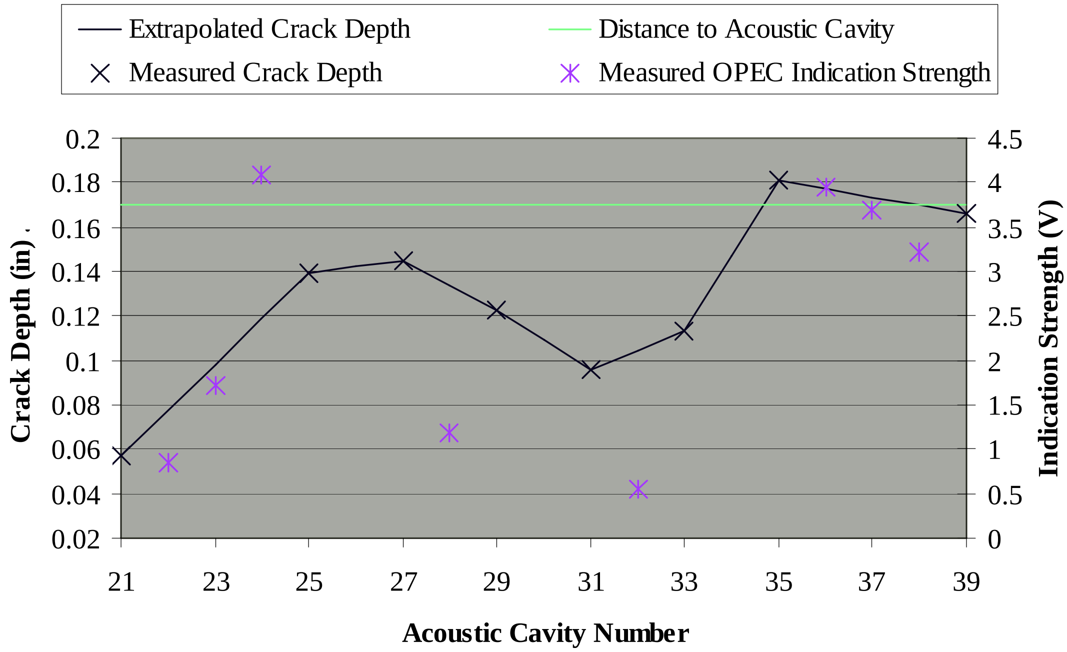

Figure 6. Inspection results for intergranular cracking in PRCS thruster S/N 132. Plot contains OPEC inspection results along with destructive analysis of thruster.

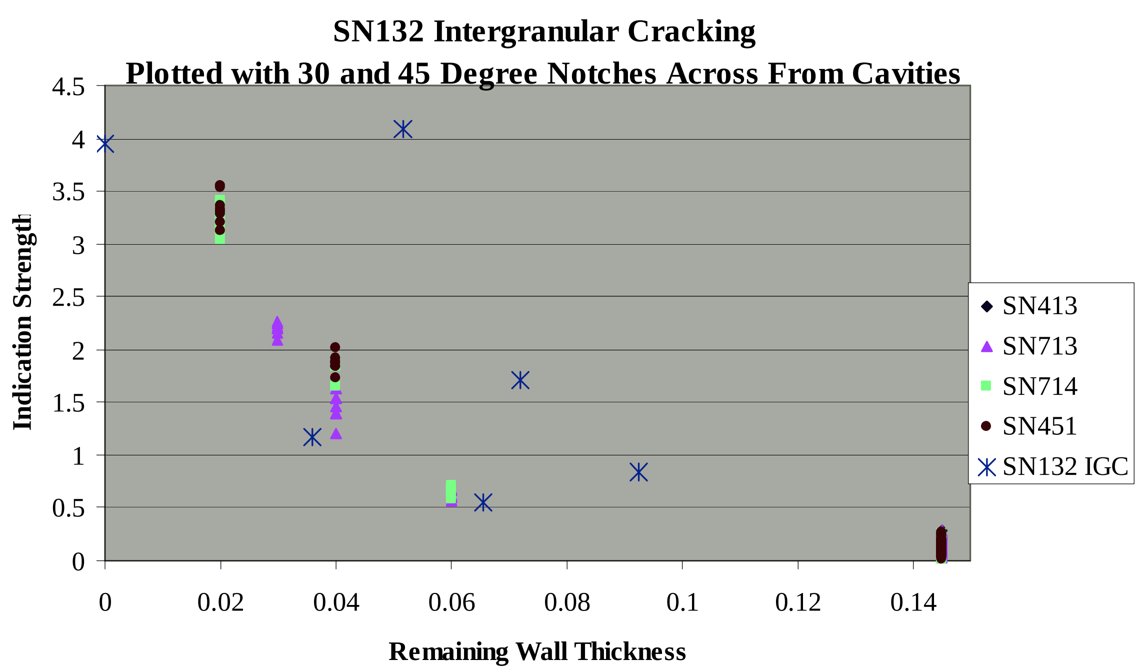

Figure 7. Plot of indication strength versus interpolated remaining wall thickness for naturally occurring interganular cracking in comparison to 30 and 45 degree notches placed across from an acoustic cavity.

Summary

An extensive validation of the orthogonal probe eddy current system for the detection of intergranular cracking in the relief radius of primary reaction control system thrusters has been performed. All flaws in the validation study with 0.040” remaining wall thickness or less were detected and no false calls were reported. In addition to remaining wall thickness, two other factors influencing the detectability of damage in PRCS thrusters have been identified as the location of the flaw (either across from or between acoustic cavities) and the angle of the flaw with respect to the acoustic cavity wall. A comparison with naturally occurring damage indicates that the most likely flaw profile produces the strongest OPEC response, comparable to the response from validation notches placed in front of an acoustic cavity at angles between 30 and 45 degrees. At this flaw orientation flaws with as much as 0.060” remaining wall thickness can be clearly separated from unflawed cavities.

The results reported here show the OPEC system to be a robust, operator independent (with sufficient training), and reliable inspection method for intergranular crack detection in the relief radius of PRCS thruster components. Deployment of the system for depot level inspections at NASA WSTF will provide valuable information and can be implemented with minimal impact on thruster processing.

Acknowledgements

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